



## INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification <sup>6</sup> : <b>B23Q 15/00, B23C 5/00, B23K 20/12</b>	<b>A1</b>	(11) International Publication Number: <b>WO 00/02704</b> (43) International Publication Date: 20 January 2000 (20.01.00)
<p>(21) International Application Number: PCT/US99/15587</p> <p>(22) International Filing Date: 8 July 1999 (08.07.99)</p> <p>(30) Priority Data: 60/092,332 9 July 1998 (09.07.98) US</p> <p>(71) Applicant: MTS SYSTEMS CORPORATION [US/US]; 14000 Technology Drive, Eden Prairie, MN 55344-2290 (US).</p> <p>(72) Inventors: CAMPBELL, Craig, L.; 13960 74th Place North, Maple Grove, MN 55311 (US). FULLEN, Mark, S.; 3 Buffalo Road, St. Paul, MN 55127 (US). SKINNER, Michael, J.; Apartment #105, 14255 Valley View Road, Eden Prairie, MN 55344 (US).</p> <p>(74) Agents: KVALE, Deirdre, M. et al.; Westman, Champlin &amp; Kelly, P.A., International Centre, Suite 1600, 900 Second Avenue South, Minneapolis, MN 55402-3319 (US).</p>	<p>(81) Designated States: CA, DE, GB, JP, NO, SE, European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE).</p> <p>Published With international search report.</p>	
(54) Title: CONTROL SYSTEM FOR FRICTION STIR WELDING		
<pre> graph LR     64[FORCE DATA INPUT COMMAND] --&gt; 60[FORCE CONTROL]     68[POSITION DATA INPUT COMMAND] --&gt; 62[POSITION CONTROL]     60 --&gt; 72[MODE SERVO]     62 --&gt; 72     72 -- 74 --&gt; 58[HEAD ACTUATOR]     58 --&gt; 52[WELDING HEAD]     52 -- 66 --&gt; 60     52 -- 70 --&gt; 62   </pre>		
<p>(57) Abstract</p> <p>A control system (50) for friction stir welding including both force and position control (60, 62). The control system mode switches (72) between position and force control based upon command parameters (64, 68) for force and position of the welding head relative to the workpiece.</p>		

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-1-

## CONTROL SYSTEM FOR FRICTION STIR WELDING

### BACKGROUND OF THE INVENTION

The present invention relates to a welding apparatus. In particular, the present invention relates to a control system for a welding head of a welding apparatus.

Friction stir welding is a process of welding component parts together using friction heat generated at a welding joint to form a plasticized region which solidifies joining workpiece sections. A welding head is used to generate friction heat along a welding joint. The welding head includes a pin that is inserted into the joint and a shoulder which is urged against an upper surface of the workpiece. The pin and shoulder spin to generate friction heat to form a plasticize region along the joint for welding operation.

For welding operation, an actuator positions the shoulder of a welding head against a workpiece and pin in the welding joint. During operation, actuator urges shoulder against the workpiece surface to generate friction heat for welding. During welding operation, it is desirable to maintain the position of a welding head relative to the workpiece surface while maintain desired force against the workpiece surface to generate friction heat. However, during operation, variations in operating parameters such as workpiece profile and thickness can alter the force and position of the welding head. These and other problems are addressed by the present invention.

### SUMMARY OF THE INVENTION

The present invention relates to a control system for a welding head. The control system incorporates both position and force control of the

-2-

welding head and mode switches between position and force control for controlling the head relative to a workpiece for welding operation.

#### BRIEF DESCRIPTION OF THE DRAWINGS

5           FIG. 1 is an embodiment of a schematic control system for controlling operation of a welding head.

FIG. 2 is a detail schematic for the control system of FIG. 1.

10           FIG. 3 is an embodiment of a schematic control system for controlling operation of a welding head.

FIG. 4 is a cross-sectional view of a welding head including an extendable pin.

FIG. 5 is a fixture for supporting a welding head for welding operation.

15           FIG. 6 is a schematic illustration of actuators for a welding head including an extendable pin.

20           FIG. 7 is a schematic illustration of a control system for a welding head including an extendable pin.

FIG. 8 is a perspective illustration of a flexible mounting fixture supporting a welding head for pitch and roll.

25           FIG. 9 is a perspective illustration of a welding fixture supporting a welding head.

#### DETAILED DESCRIPTION OF THE ILLUSTRATIVE EMBODIMENTS

30           FIG. 1 schematically illustrates an embodiment of a control system 50 for friction welding application. As shown, control system 50 operates a welding head 52 for welding two members along a joint as will be explained. Welding probe 50 is connected to a spindle drive 54 to rotate probe 50 for welding operation. Rotation of the welding head 52 generates friction heat to create a plasticize region for welding workpiece

-3-

sections. Welding head 52 is positioned relative to the workpiece by a head actuator 58. Actuator 58 supplies a forging force to urge the welding head 52 against an upper surface of the workpiece to engage the workpiece and generate friction head for welding.

As shown in FIGS. 1-2, control system 50 controls actuator 58 based upon position and force control 60, 62. Force control 60 includes input force or force command 64 and force feedback 66 from the welding head 52. Force command 64 is a preset or predefined forging force of the welding head 52 against the workpiece surface and the feedback 66 is the actual force of the welding head 52 against the workpiece surface. Position control 62 includes input position or position command 68 and position feedback 70. Input position or command 68 is a pre-set operation position for the welding head 52 to position or locate the welding head 52 relative to the workpiece surface and position feedback 70 is the actual position of the welding head 52.

Force and position control 60, 62 are coupled to a mode controller 72 for selectively controlling actuator 58 based upon force or position control. An actuator control signal 74 or command operates head actuator 58 based upon force and position control. Mode controller 72 switches mode control between force and position control 60, 62 based upon the force and position error between the command position and force 64, 68, and feedback 66, 70. For example, mode controller switches provides force control to maintain force feedback relative to command parameters and switches from force to position control when force feedback is within command parameters. Mode control provides position control to maintain position feedback

-4-

within command parameters and switching to force control when position feedback is within command parameters. Preferably mode controller includes a proportional integrated derivative (PID) controller for position and  
5 force control and "bumpless" mode switching between force and position control.

In the embodiment illustrated in FIG. 3, a mode control system is used to actuate a welding head having a slidable pin 80 coupled to a probe member 82  
10 having a shoulder 84 urged against an upper surface of a workpiece 86. As shown pin 80 is slidable coupled as illustrated by arrow 88 to probe member 82 to insert pin 80 in joint 90 between workpiece sections 86-1, 86-2 for welding workpiece sections 86-1, 86-2. As shown, an  
15 shoulder actuator 92 operates probe member 82 to urge shoulder 84 against the workpiece surface to generate friction heat and pin actuator 94 operates pin 80 to extend the depth of the workpiece for welding.

Control system includes a shoulder actuator  
20 controller 96. Shoulder actuator controller 96 includes position and force control to control the position of shoulder 84 relative to the workpiece surface and maintain desired force on the workpiece surface. As shown, position control includes a position command or  
25 input 98 related to elevation of the shoulder for engagement with the upper surface of the workpiece 86 and shoulder position feedback 100. Force control includes a force command or input 102 related to a pre-set force for actuating the shoulder 84 against the  
30 workpiece 86 and a force feedback 104. A mode controller 106 supplies a shoulder actuator command 108 based upon position and force control as previously explained. For example, mode controller 96 switches between force and position control to maintain a limit

-5-

or welding force on the workpiece and maintain limit separation distance between shoulder 84 and a backplate (not shown in FIG. 3) supporting the workpiece. For example, limit separation can be a minimum separation or extension distance of pin 80 based upon workpiece thickness.

Control system includes a pin actuator controller 108 including position and force control to maintain the position or depth of the pin 80 relative to the workpiece surface. Pin depth should extent sufficient thickness to limit stress notches in the joint. As previously explained, in welding operations, workpiece is supported on a backplate and extension of the pin close to the backplate can weld the workpiece to the backplate. Thus controller 108 maintains the depth of the pin 80 for desired welding operation.

As shown, position control includes a position command or input 110 related to pin position or depth and pin position feedback 112. Force control includes a force command or input 114 related to a pre-set force of the pin and force feedback 116. Force feedback 116 senses contact of the pin with the backplate for pin 80 extension control. Mode controller 118 supplies a pin actuator command 120 based upon position and force control to maintain limit position and forced based upon position and force commands. For example, position command may include limit pin extension based upon workpiece thickness and limit force to detect contact with the back plate.

FIG. 4 is a detailed cross-sectional view of an embodiment of a welding head including a slidable pin 80. In the embodiment shown, head includes an outer housing 122 and an inner housing 124 rotationally connected to outer housing by bearings 125. Probe

-6-

member 82 and shoulder 84 are formed by inner housing 124. Pin 80 is slidably supported in housing 124 via rod 126. Spindle shaft 128 is coupled to housing 124 to rotate housing 124 (probe member 82 and pin 80) by operation of spindle drive 54 for welding operation. In one embodiment, spindle drive 54 includes an inline torque transducer for spindle control. Spindle control includes simultaneous torque and RPM (revolutions per minute) control.

10           As shown schematically, shoulder actuator 92 is coupled to outer housing 122 to position and actuate probe member 82. In the embodiment shown, pin actuator 94 is a fluid actuator supported in inner housing 124 and coupled to rod 126 connected to pin 80. Fluid  
15   actuator includes an actuation chamber 130 and piston 132. Rod 126 is connected to piston 132 operable in chamber 130. Actuator fluid is delivered to chamber 130 from fluid source 134 for bi-directional movement as illustrated by arrow 88. Fluid is delivered from fluid  
20   source 134 to rotating housing 124 by fluid commutator or slip rings 138. Fluid is delivered through channels 140, 142 for bi-directional actuation as illustrated by arrow 88. Preferably, fluid source 134 is a hydraulic fluid, although alternate actuator fluids can be used.

25           Although a fluid actuator is shown, application is not limited to a fluid actuator and alternate actuators can be used such as an electrical or mechanical actuator with a fluid or electrical actuator interface, between the rotating probe member 82 and  
30   stationary housing for actuation. In the embodiment shown, cooling fluid is supplied from a cooling fluid source 144 to channels 146 in the head through fluid commutator 138 for temperature control during welding operation. Housing 122 includes upper and lower



-7-

portions separated by a sealing ring 148 for operating fluid containment. A displacement sensor 150 (for example, a linear voltage displacement transducer "LVDT") is coupled to rod 126 for position feedback control for pin 80 extension.

As shown in FIG. 5, for welding operation, probe housing 122 is supported for movement along a probe track 152 supported by a welding frame 154. Frame includes a base 156, and posts 160, 162 which extend from base 156 to support probe track 150 above a workpiece table or backplate 164. Probe track 152 is movably coupled to tracks 166, 168 along posts 160, 162 to raise and lower the welding head as illustrated by arrow 170. As described, probe track 152 supports head for movement along a welding joint of a workpiece supported by table 164 as illustrated by arrow 174.

Fluid actuators 176, 178 are coupled to probe track 152 to raise and lower track 152 and welding head as illustrated by arrow 170. Actuators 176, 178 position welding head relative to workpiece and supply forging force to probe member 80 through housing 122. Table 164 can be movably supported relative to base as illustrated by arrows 180 for head placement along a welding joint. Bi-directional placement of the probe as illustrated by arrows 180 facilitates complex welding operation in addition to straight line welding. Operation of the actuators 176, 178 can be independently controlled to vary angle 184 of the head and track 152 for various welding operations. Although a particular fixture is shown, application is not limited to the particular fixture.

As shown schematically in FIG. 6, force feedback 104 for probe member 82 is measured by force transducer 188 connected in series with shoulder

-8-

actuator 92 (fluid actuators 176, 178). Force feedback 116 for pin 80 is measured by a pressure sensor assembly for measuring pressure differential between chamber portions 190, 192 of fluid actuator. Although  
5 particular force feedbacks 104, 116 are described, force feedback 104, 116 is not limited to the particular embodiment described. Position feedback 112 for pin 80 is measured by displacement sensor 150 and position feedback for probe member 82 can be provided by a  
10 position sensor (such as a LVDT) coupled to probe member 82 as illustrated schematically by block 194.

Although application of the force-position control system has been described with respect to specific welding head design, application is not limited  
15 to the specific designs shown. The control system can be used to weld parts having varied thickness and profile based upon force and position commands in addition to parts having a flat surface. In particular, as illustrated in FIG. 7, position control commands 98,  
20 110 is based upon workpiece profile data 200. Workpiece profile data can be measured or downloaded off-line or during the welding process by various sensors such as optical sensors for providing thickness and surface contour data for the workpiece. For example, workpiece  
25 profile data 200 can include thickness and boundary surface data for deriving position command for  $z_u$  (position for shoulder 84 relative to upper surface of the workpiece) and  $\Delta z$  (extension of pin 80 which is a function of the workpiece thickness) for shoulder and  
30 pin actuators 92, 94.

As shown in FIG. 7, welding surface 206 is sloped or inclined. In FIGS. 8 and 9, head is flexibly supported to pitch and roll to adjust shoulder 84 normal to the workpiece surface for contour welding or welding

-9-

a sloped surface. Head is flexibly supported relative to an x axis by first and second frame members 210, 212. Head 50 is pivotally connected first frame member at trunions 214 to roll relative to the x-axis as  
5 illustrated by arrow 216. Frame member 210 is pivotally connected to frame member 212 to support the head 50 to pitch as illustrated by arrow 218.

As shown in FIG. 9, pitch and roll actuators 220, 222 adjust the position of the head 50 so that the  
10 surface of the head shoulder 84 is normal to the surface of the workpiece for contour welding or welding inclined or sloped surfaces. Profile data 200 (including contour data) can be used to control pitch and roll actuators 220, 222. Stop block 224 provides a limit position for  
15 the welding head.

Although the present invention has been described with reference to preferred embodiments, workers skilled in the art will recognize that changes may be made in form and detail without departing from  
20 the spirit and scope of the invention.

-10-

WHAT IS CLAIMED IS:

1. A welding apparatus comprising:  
a welding head adapted to engage a workpiece  
for welding;  
an actuator coupled to the welding head;  
a force controller operably coupled to the  
actuator for force control;  
a position controller operably coupled to the  
actuator for position control; and  
a mode controller coupled to the force and  
position controller to mode switch  
between force and position control for  
mode control.
2. The welding apparatus of claim 1 including  
force feedback coupled to the force controller for force  
control.
3. The welding apparatus of claim 2 wherein the  
force controller controls actuator based upon command  
force and force feedback.
4. The welding apparatus of claim 1 including  
position feedback coupled to the position controller for  
position control.
5. The welding apparatus of claim 4 wherein the  
position controller controls actuator based upon command  
position and position feedback.
6. The welding apparatus of claim 5 wherein  
command position is derived based upon the profile data  
of a workpiece.
7. The welding apparatus of claim 6 wherein the  
profile of the workpiece is contoured and profile data  
includes at least of thickness or boundary surface data.
8. The welding apparatus of claim 3 wherein the  
mode controller operates mode switching based upon a

-11-

force error where force error is a function of command force and feedback force.

9. The welding apparatus of claim 5 wherein the mode controller operates mode switching based upon position error where position error is a function of the command position and the feedback position.

10. The welding apparatus of claim 1 including a proportional integrated derivated controller for position, force and mode control.

11. The welding apparatus of claim 1 wherein the welding head includes a probe member including a shoulder and a pin slideably supported relative to the probe member and a probe actuator and pin actuator including position and force control and a mode controller coupled to the force and position control for the probe actuator and pin actuator to mode switch between position and force control.

12. A method for welding a workpiece comprising steps of:

operating a welding head to position the welding head proximate to a workpiece and supply a force to the welding head to engage the workpiece; and  
controlling operation of the welding head based upon position and force control.

13. The method of claim 12 further comprising the step of:

mode switching between force and position control.

14. The method of claim 12 further comprising the steps of:

measuring force on the welding head; and  
using the measured force for force control.

-12-

15. The method of claim 12 further comprising the steps of:

sensing position of the welding head; and  
using the sensed position for position control.

16. The method of claim 12 wherein the welding head includes a probe member having a shoulder and a pin slideably coupled to the probe member and further comprising the steps of:

controlling operation of the probe member and pin based upon position and force control.

17. The method of claim 16 further comprising the steps of:

measuring force on the probe member; and  
using the measured force for force control.

18. The method of claim 16 further comprising the steps of:

sensing position of the probe member; and  
using the sensed position for position control.

19. The method of claim 16 further comprising the steps of:

measuring force on the pin; and  
using the measured force for force control.

20. The method of claim 16 further comprising the steps of:

sensing position of the pin; and  
using the sensed position for position control.

-13-

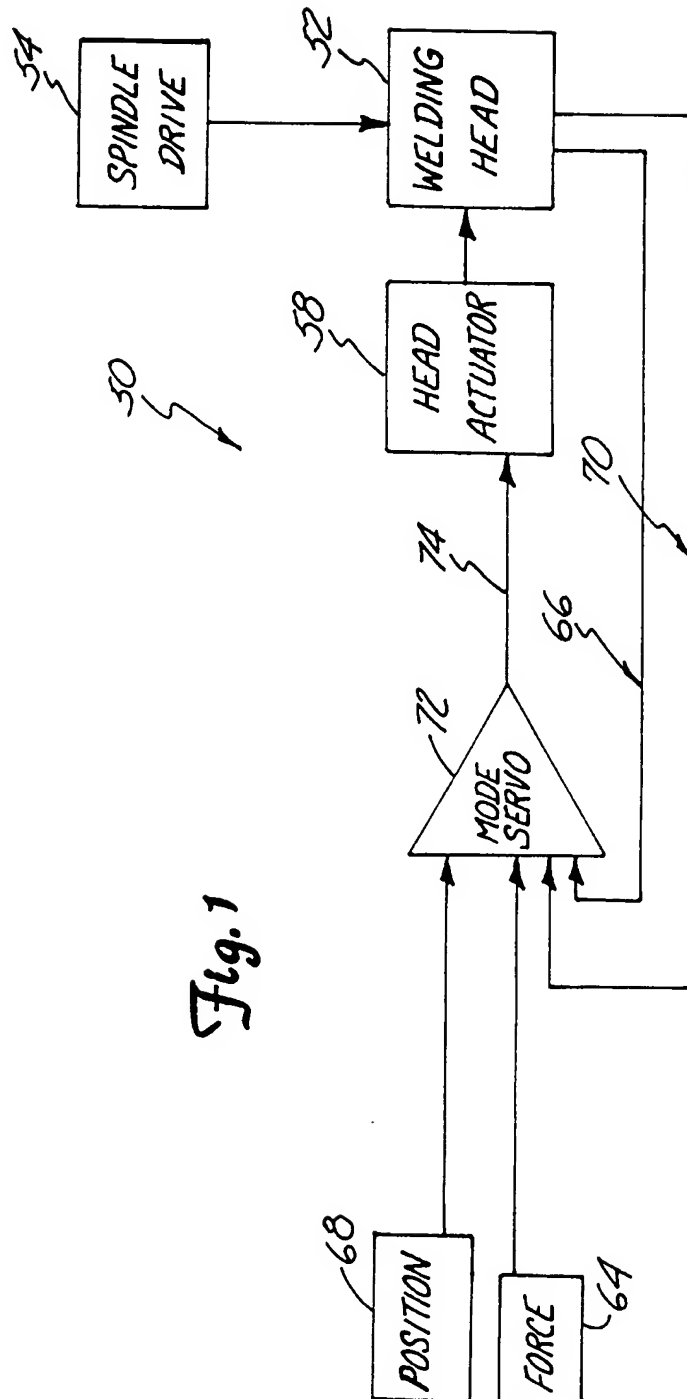
21. The method of claim 13 and comprising the steps of:

switching between position control to force control when position feedback is within the position command.

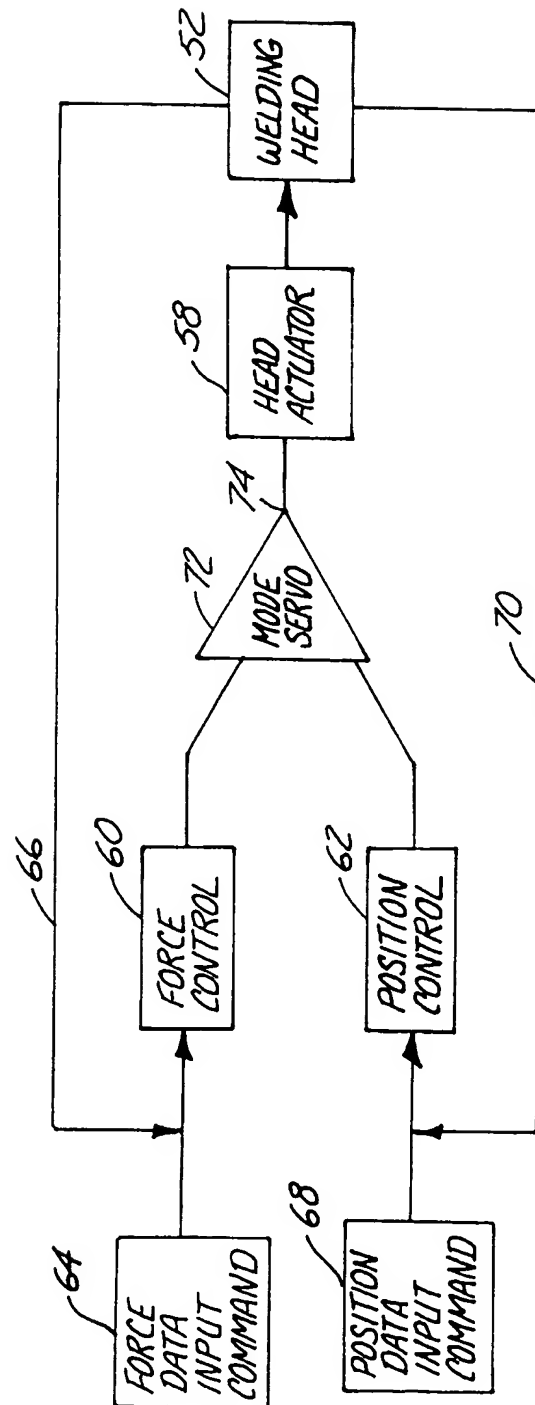
22. The method of claim 13 and comprising the steps of:

switching between force control to position control when force feedback is within the force command.

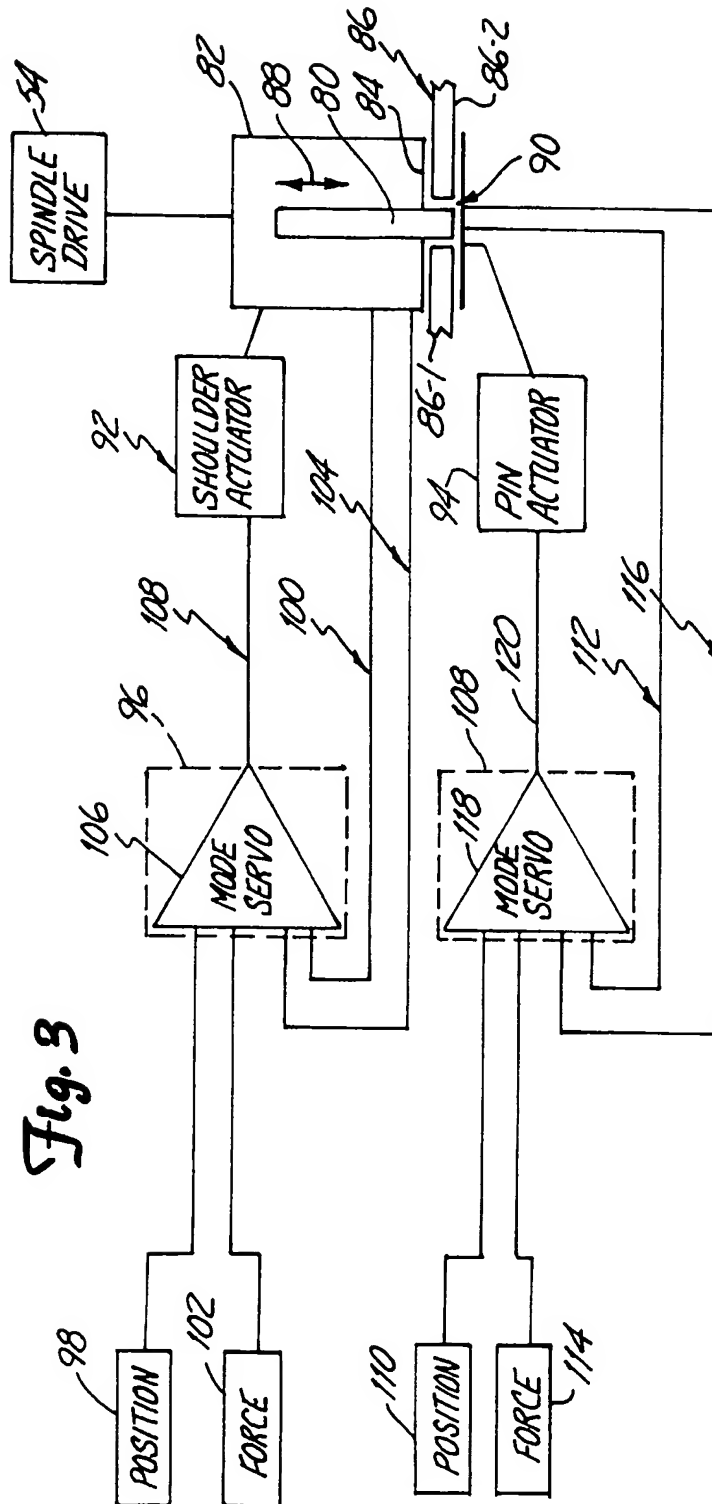
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*Fig. 2*

3/9



4/9

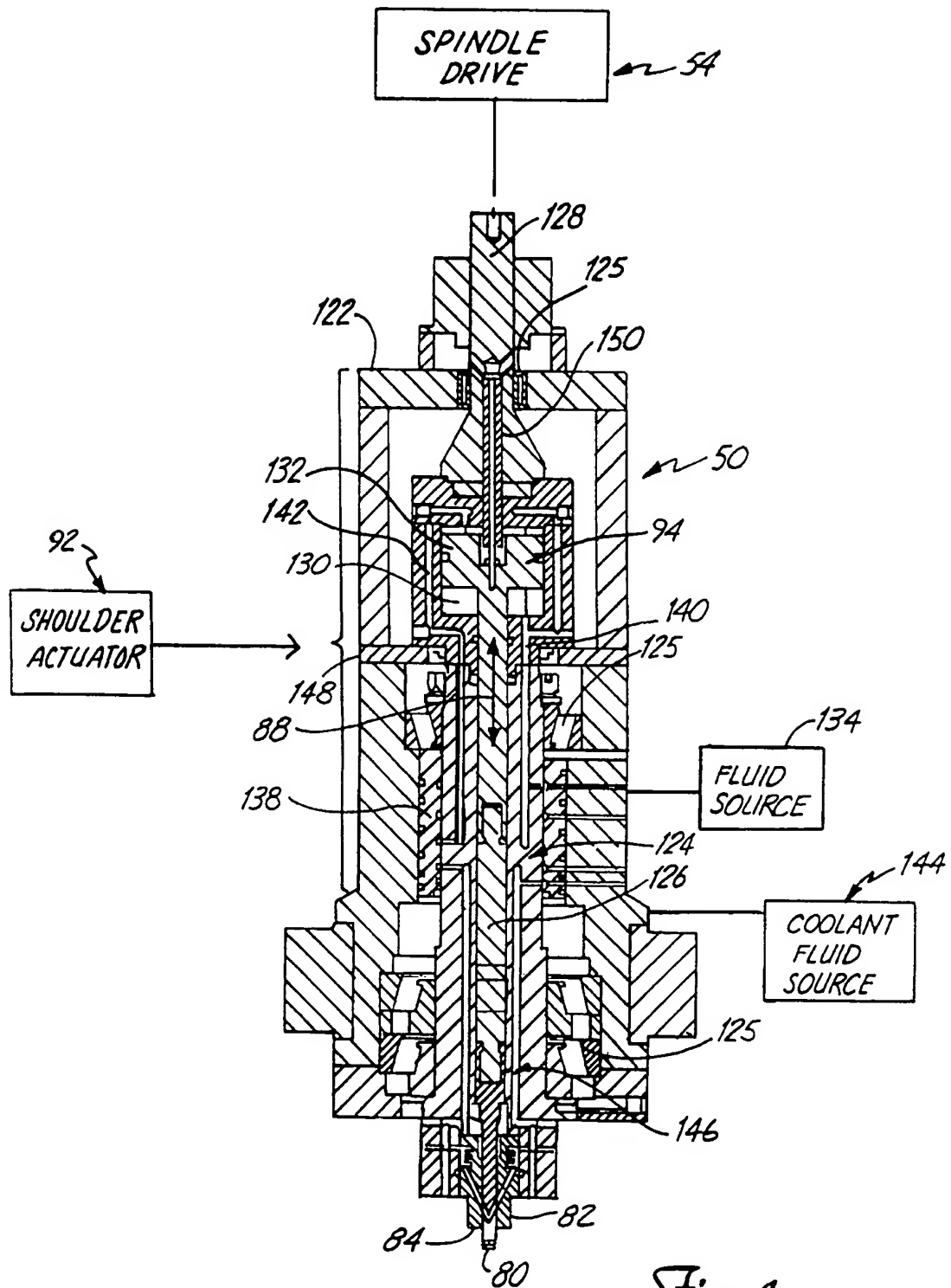
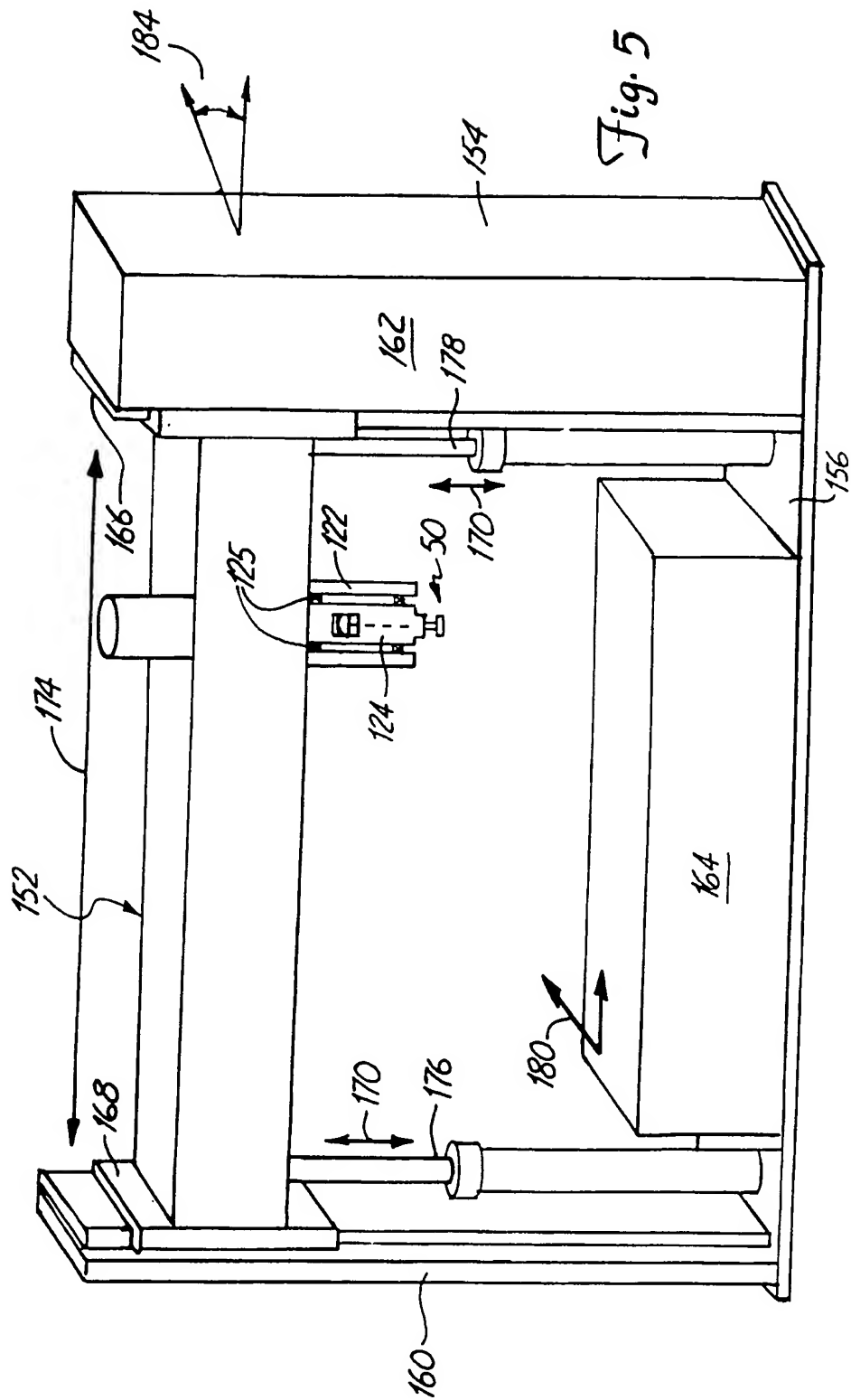
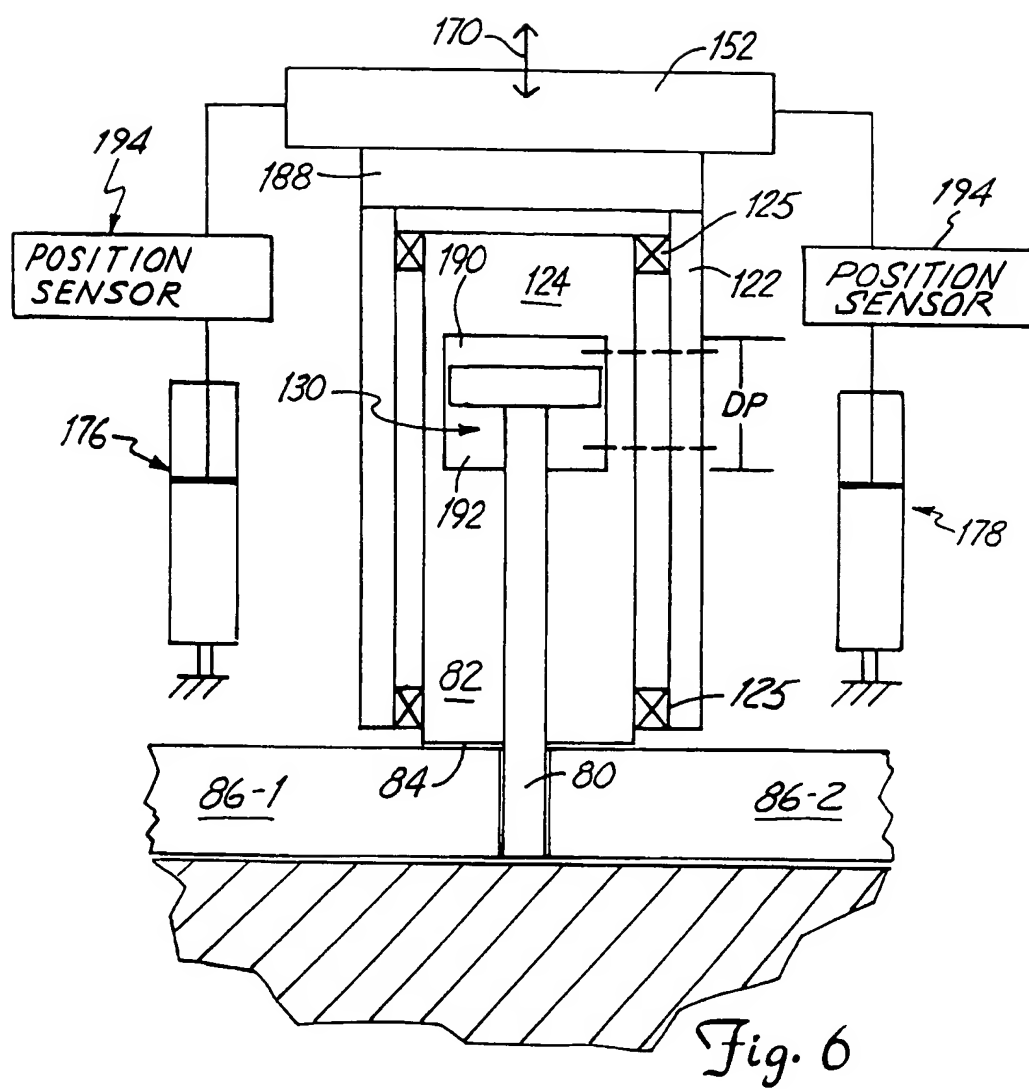


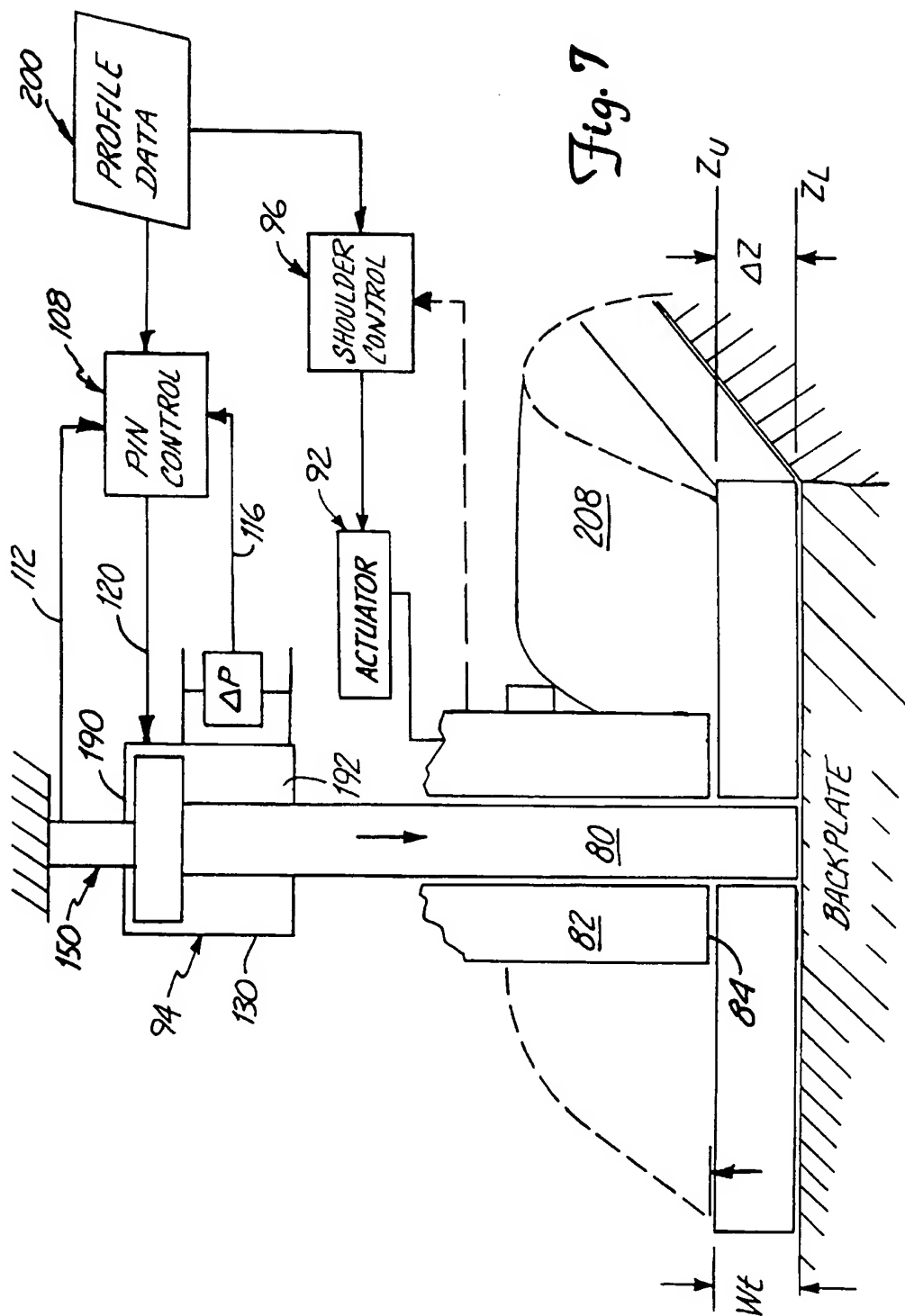
Fig. 4

5/9



6/9





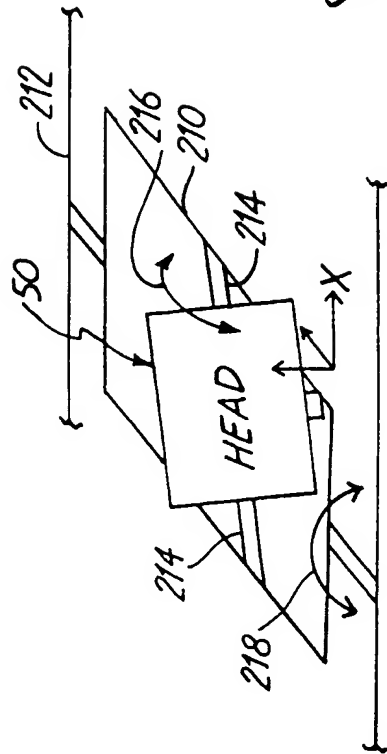


Fig. 8





## INTERNATIONAL SEARCH REPORT

International application No.

PCT/US99/15587

**A. CLASSIFICATION OF SUBJECT MATTER**

IPC(6) : B23Q 15/00; B23C 5/00; B23K 20/12

US CL : 228/2.1, 112.1; 144/134.1, 142, 356

According to International Patent Classification (IPC) or to both national classification and IPC

**B. FIELDS SEARCHED**

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 228/2.1, 112.1; 144/134.1, 142, 356

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

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APS; WEST

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y,P	US 5,893,507 A (DING et al) 13 April 1999, col. 2, lines 14-16 and 47-52, col. 3, lines 1-20, col. 5, lines 16-20, and abstract.	1, 3, 4, 5, 9, 10, 12, 13, 14, 15, 17, 18, 19, 20, 21, 22
Y	US 5,518,562 A (SEARLE et al) 21 May 1996, col. 2, lines 36-47, col. 9, lines 33-62, and figures 1 and 2.	1, 2, 8, 11, 16
A	US 5,558,265 A (FIX, JR) 24 September 1996.	1
A	US 5,486,262 A (SEARLE) 23 January 1996.	1
A	US 5,697,544 A (WYKES) 16 December 1997.	1
A	US 3,817,439 A (KIWALLE et al) 18 June 1974.	1

☐ Further documents are listed in the continuation of Box C.
 ☐ See patent family annex.

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